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Pedro Victor Borges Caldas da Silva, Chantal Taconet, Sophie Chabridon, Denis Conan, Everton Cavalcante, et al.. Energy awareness and energy efficiency in internet of things middleware: a systematic literature review. *Annals of Telecommunications - annales des télécommunications*, 2022, 78 (1-2), pp.115-131. 10.1007/s12243-022-00936-5 . hal-03901655

HAL Id: hal-03901655

<https://hal.science/hal-03901655v1>

Submitted on 24 Mar 2023

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Energy-awareness and energy efficiency in Internet of Things middleware: A systematic literature review

Pedro Victor Borges Caldas da Silva · Chantal Taconet · Sophie Chabridon · Denis Conan · Everton Cavalcante · Thais Batista

Received: 26 January 2022 Accepted: 26 November 2022 Published: 15 December 2022

Abstract The Internet of Things (IoT) is characterized by a myriad of physical devices, together with high heterogeneity in both software and hardware. Middleware platforms have been proposed in order to alleviate such heterogeneity, providing relevant services and easing application development. In IoT systems, energy consumption is a key concern due to the proliferation of devices and their limited battery capacity. IoT middleware platforms can play an important role in providing applications with strategies, and support, for energy-awareness and energy efficiency. Although there is a significant existing body of work related to IoT middleware, there is, as yet, no complementary overview of the state-of-the-art on how these platforms can contribute to energy efficiency and energy-awareness in IoT systems. This paper provides such an overview in the form of a systematic literature review (SLR). The SLR was

carried out by following a systematic, rigorous procedure to search, select, and analyze primary studies available in the literature. Our corpus, as presented in this paper, is made up of twenty-two such studies, each presenting strategies and solutions on middleware support for energy efficiency and energy-awareness in IoT systems. These strategies mainly focus on network adaptation, task offloading, and concrete implementations. However, most of these studies do not consider energy-aware/efficiency abstractions, and focus on solutions working at the end-user application side. In conclusion, this paper also raises relevant challenges and potential directions for further research resulting from the main SLR findings.

Keywords Internet of Things · Middleware · Energy-awareness · Energy efficiency · Green Computing · Systematic literature review

This work is a contribution to the Energy4Climate Interdisciplinary Center (E4C) of IP Paris and École des Ponts ParisTech, supported by 3rd Programme d'Investissements d'Avenir [ANR-18-EUR-0006-02]. It has been funded by the "Futur & Ruptures" program from Institut Mines Télécom, Fondation Mines-Télécom and Institut Carnot.

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1 Introduction

The *Internet of Things* (IoT) is an umbrella term referring to smart objects, services, and applications that seamlessly collaborate to provide value-added information and functionalities for end-users and systems. One of the main characteristics of the IoT is the possibility of connecting almost every single object on Earth to the Internet, leading to predictions for hundreds of billions of connected devices in the next decade [2, 15].

A remarkable characteristic of the IoT is the high hardware and software heterogeneity, encompassing devices with different capabilities, functionalities, and network protocols. *IoT middleware platforms* have been proposed in recent years to address such heterogeneity whilst abstracting away specific details of devices from applications and users, promoting interoperability, and providing services and interfaces to leverage application development [6, 23, 29].

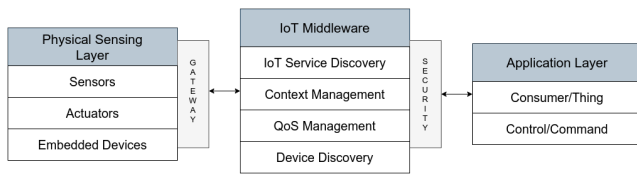


Fig. 1 The IoT system basic architecture [41]

IoT middleware can be seen as a software layer residing between the application and physical sensing layers (see Fig. 1) to provide: (i) abstractions for accessing physical devices and managing data produced by them, thereby enabling developers to focus on the application development; (ii) virtualization and aggregation of devices into IoT platforms; (iii) support for interactions between devices and users; and (iv) interoperability for managing hardware and software entities [26,38]. Moreover, IoT applications can benefit from such middleware, offering functionalities such as data analytics and visualization, actuation, etc.

As the number of IoT devices extends into the billions, this represents a paramount concern with respect to the growing global energy demand for Information Technology; which is estimated to reach 7.335 TWh/year by 2025. This is twice the estimated consumption in 2015 [13], raising important issues that could impact the future development of IoT systems. On the one hand, IoT devices typically are battery-limited, so applications need to rely on strategies and infrastructure that promote judicious use of devices. On the other hand, the proliferation of devices makes energy efficiency an imperative requirement for applications. In both cases, IoT middleware platforms can play a relevant role in making applications developed upon them become more energy-aware and more efficiently use energy resources. This can be achieved by making middleware provide more information concerning what resources are being used by an application, such as network interface (Wi-Fi, Ethernet, Bluetooth), GPS, amount of exchanged data, etc.

Noureddine et al. [31] highlight that middleware could contribute to optimizing or reducing the energy consumption of hardware devices, software services, and the platform itself. IoT middleware platforms should not solely consider energy efficiency as a non-functional requirement. Instead, it needs to be at the solution's core, as the middleware is expected to be shared by many applications and offer facilities to ease application development. IoT end-user applications need to work with green protocols and algorithms to ensure that energy consumption is kept *at a minimum* for the expected functionalities. This idea becomes feasible through the development of an energy-efficient middleware which provides the necessary services for meeting such requirements.

In this context, it is also important to consider energy-awareness, i.e., understanding the energy consumption and

its efficiency [16]. With an energy-aware IoT middleware, an IoT system could know the energy efficiency of the components from which it is composed, significantly easing the task of decreasing energy consumption. This capability is also relevant considering that application developers often have limited knowledge on how much energy their software consumes and which parts use the most energy [33].

The literature presents many studies related to green IT and energy-awareness in Big Data [45,47], communication technologies [5,8,27,46], industry [40,44], and energy-saving techniques [12,39]. However, there is, as yet, no study offering an overview of the state-of-the-art on how middleware platforms can contribute to energy efficiency and energy-awareness in IoT systems. Such an overview, as presented in this paper, can enable researchers and practitioners to critically reflect on the current state-of-the-art and identify critical issues to drive future research on energy requirements in IoT systems. As such, this paper provides a systematic literature review (SLR) on energy-awareness and energy efficiency in IoT middleware. The SLR was carried out by following a systematic, rigorous procedure that followed well-established guidelines for collecting, selecting, and analyzing primary studies while proving scientific value to the obtained findings [21,36].

The SLR presented in this paper aimed to investigate: (i) what is currently provided at the middleware level to better manage the energy consumption of IoT systems; (ii) which abstractions exist at the IoT middleware level to enable energy-awareness; (iii) how existing proposals have been evaluated and their maturity; and (iv) how to deploy IoT middleware with different strategies for limiting energy consumption and enabling energy efficiency in IoT systems. The corpus is made up of twenty-two papers published in journals, conferences, and workshops. As well as reporting on the main findings of the SLR, this paper highlights relevant issues to be addressed by future work on energy-awareness and energy efficiency in IoT middleware.

The remainder of this paper is organized as follows. Section 2 provides the background of this work concerning proposals for green IoT middleware. Section 3 presents the research methodology adopted for carrying out the SLR. Section 4 synthesizes the analysis of the selected corpus in order to answer the research questions. Section 5 discusses some important issues that can drive further research in this context. Section 6 assesses some threats to the validity of this work. Finally, Section 7 offers some concluding remarks.

2 Related work

Energy-saving proposals started mainly with hardware before considering software [7]. Since then, many studies have addressed energy efficiency related to software, such as the

impact of programming languages and data structures [32, 35], and the study of parallel programming frameworks [37].

Balaji et al. [3] pointed out that a relevant challenge in IoT technologies is the amount of energy used by the vast number of devices. Javed et al. [19] presented a survey on operating systems for connected objects and mentioned energy efficiency as a significant concern when conceiving these systems. Shaikh et al. [39] state that the increase in the number of connected objects represents a critical issue in IoT systems. They consider that *green techniques* such as tethering, multi-hopping, and the mobility of users and objects in a network could be used to foster *green communication* among these objects.

Several studies have evaluated popular IoT protocols aiming to identify how applications can improve their energy efficiency. Joshi et al. [20] presented a comparison of MQTT, COAP, and HTTP and concluded that MQTT under a high rate of messages per hour would be the best protocol for energy-efficient applications and HTTP would be the worst option. Colitti et al. [9], Bandyopadhyay et al. [4], and Dizdarević et al. [10] obtained similar results. Luzuriaga et al. [24] concluded that MQTT would be suitable for energy-constrained environments, even though AMQP is more reliable and scalable.

Noureddine et al. [31] studied energy management at the middleware level, but not specifically in the IoT context. They selected and analyzed 12 middleware platforms with respect to (i) energy optimization techniques at the architectural level, (ii) energy-efficient protocols provided by the middleware, (iii) energy-aware algorithms [28,42], and (iv) energy-aware models for middleware. They concluded that contributions are lacking for energy management middleware using autonomic approaches and generic approaches. In contrast, this paper provides a systematic mapping of the literature on IoT middleware, focusing on proposals that provide energy-efficient/aware mechanisms and showing the state-of-the-art in dealing with energy management.

The afore-mentioned works focus on energy-saving in IoT operating systems for connected objects, network protocols, and data levels, whereas this SLR focuses on energy concerns at the middleware level for IoT systems. Although many studies support technologies required to provide IoT systems with energy efficiency, the link between those technologies and IoT middleware needs to be further elaborated. Moreover, middleware is a central part of IoT systems, but energy efficiency at that level is still an emergent area. The SLR presented in this work investigates energy-awareness and efficiency mechanisms provided by middleware to improve energy efficiency in IoT systems.

3 Research methodology

The SLR presented in this paper was carried out following well-defined, consolidated guidelines [22,36]. Three basic steps were followed: (i) *planning*, which gives rise to a protocol defining the research questions to answer, the search strategy to be adopted, the criteria to be used to select primary studies, and the data extraction and synthesis methods; (ii) *execution*, in which studies are identified, selected, and analyzed according to the protocol; and (iii) *reporting*, which aggregates information extracted from relevant studies considering the research questions and outlines conclusions based on them.

Research questions. Four research questions (RQs) were proposed aiming at finding primary studies to understand and summarize pieces of evidence about energy-efficiency and energy-awareness in IoT middleware:

RQ1: How energy-efficiency has been addressed by IoT middleware?

Rationale: To identify proposals that consider energy efficiency in IoT middleware.

RQ2: What abstractions are provided by middleware for enabling energy-awareness or energy efficiency of IoT systems?

Rationale: To identify any synergy between IoT middleware and applications built upon them either for energy-awareness or energy-efficiency transparently provided by middleware.

RQ3: How have existing energy efficiency proposals been evaluated?

Rationale: To identify how to measure or evaluate energy consumption within the many components of an IoT system.

RQ4: Which part/component of the distributed architecture is considered in the middleware solution for energy efficiency?

Rationale: To identify where the IoT middleware is deployed, what is measured, and for which component of an IoT system the energy consumption is reduced.

Answering RQ1 aims to result in a catalog of strategies and techniques that have been used so far in IoT middleware for energy efficiency. Answering RQ2 gathers data about how the research community deals with the software level when considering middleware, energy-awareness and energy efficiency. Answering RQ3 gathers knowledge on how the energy efficiency of IoT middleware and systems built with their support have been evaluated. Answering RQ4 aims to provide information on where energy-related measurements are made and which components are affected by the energy efficiency techniques adopted by IoT middleware platforms.

Search strategy. An automated search process was carried out over five electronic publication databases to retrieve relevant studies to answer the posed RQs. The used databases were: IEEEExplore¹, ACM Digital Library², Scopus³, Science Direct⁴, and Web of Science⁵. These sources are among the most popular publication databases in Computer Science and Engineering and have good coverage of the literature [11,22]. Other relevant criteria were the quality of the results returned by the automated search procedure, the availability of the full text of the studies, ease of use, up-to-dateness of contents, and versatility to export results.

Based on the defined RQs, three main terms were initially identified, namely *Internet of Things*, *middleware*, *energy efficiency*, and *energy-awareness*. The following search string was built considering synonyms and alternative terms:

middleware AND (energy consumption OR energy efficiency OR energy awareness OR green) AND (Internet of Things OR IoT)

Selection criteria. Selection criteria were used to assess the relevance of each primary study to answer the established RQs. Inclusion criteria define circumstances that make a study relevant, whereas exclusion criteria exclude studies that are unrelated to the RQs. Four inclusion criteria (ICs) and five exclusion criteria (ECs) were defined. In this work, a given primary study was regarded as relevant if it did not meet any EC and met at least one IC.

- IC1: The study addresses energy efficiency or energy-awareness in the IoT context.
- IC2: The study presents an energy efficiency proposal relying on middleware or middleware models.
- IC3: The study presents a proposal to reduce energy consumption in IoT applications or middleware.
- IC4: The study concerns software that connects systems to reduce energy consumption.
- EC1: The study is not related to IoT or middleware platforms in this context.
- EC2: The study is a previous version of a more recent study on the same research.
- EC3: The study does not have an abstract, or the full text is unavailable.
- EC4: The study is a table of contents, foreword, tutorial, editorial, keynote talk, or summary of conference/workshop.
- EC5: The study is not written in English, the most common language in scientific papers.

¹<http://ieeexplore.ieee.org>

²<http://dl.acm.org>

³<http://www.scopus.com>

⁴<https://www.sciencedirect.com/>

⁵<https://www.webofknowledge.com/>

Data extraction. A data extraction sheet was built with items related to the RQs and other relevant information to extract data from the selected primary studies. Besides basic information such as the title, publication year, and venue, extracted data was concerned with (i) the proposal of the presented middleware, (ii) where the middleware is deployed, (iii) the impact of the energy efficiency strategy, (iv) the metrics used to evaluate the middleware, and (v) where the energy consumption is measured.

Selection process. The search and selection processes considered primary studies published up to and including June 2022. In the automated search process, the search string has undergone minor changes to make it compatible with the specificities of each database engine. Next, the automated search procedure was performed over each electronic database according to the adapted search string. The search procedure was limited to title, abstract, and keyword fields.

Fig. 2 depicts the steps to select the relevant primary studies. The automated search procedure over the five electronic databases retrieved 237 results. Duplicates were removed, thus resulting in a set with 167 studies. These studies were submitted to a preliminary selection based on the selection criteria applied to the title, abstract, and keywords. Whenever the relevance of a study was in doubt, both the introduction and conclusion sections were also analyzed. This resulted in a set of 114 studies. ECs played a significant role in removing studies that would not be relevant for this SLR. Forty-five results were excluded for being unrelated to IoT or middleware (EC1), and eight results were excluded because they did not represent a primary study (EC4). No results were removed for the other ECs.

The snowballing technique [18], which uses the reference list of a study or citing references to identify additional studies, was applied to each full-read selected study to retrieve additional studies. The snowballing resulted in the inclusion of one additional study. Another additional study identified by experts⁶ and not retrieved in the previous steps was included in the set of potentially relevant studies. The remaining 116 studies were analyzed in full regarding their conformance to the selection criteria of this SLR. The final set contained 22 studies selected for data extraction. The number of relevant studies seems to be low since energy efficiency and energy-awareness in IoT middleware are recent topics but worthwhile investigating for future research. Table 1 lists the selected studies, identified as S1 to S22. Interested readers can go to Appendix A for a summary of each selected study.

⁶An expert is a researcher with experience in both IoT middleware and energy-efficiency strategies.

Table 1 List of selected studies

ID	Reference	Citation count (Google Scholar, Sept. 2022)
S1	Aazam, M., Islam, S.U., Lone, S.T., Abbas, A.: Cloud of Things (CoT): Cloud-Fog-IoT task offloading for sustainable Internet of Things. <i>IEEE Transactions on Sustainable Computing</i> 7 (1), 87–98 (2022)	11
S2	Song, Z., Le, M., Kwon, Y.-W., Tilevich, E.: Extemporaneous micro-mobile service execution without code sharing. In: <i>Proceedings of the 37th IEEE International Conference on Distributed Computing Systems Workshops</i> , pp. 181–186. IEEE, USA (2017)	3
S3	Kalbarczyk, T., Julien, C.: Omni: An application framework for seamless device-to-device interaction in the wild. In: <i>Proceedings of the 19th International Middleware Conference</i> , pp. 161–173. ACM, USA (2018)	8
S4	Al-Roubaiey, A., Sheltami, T., Mahmoud, A., Yasar, A.: EATDDS: Energy-aware middleware for wireless sensor and actuator networks. <i>Future Generation Computer Systems</i> 96 , 196–206 (2019)	7
S5	Akkermans, S., Bachiller, R., Matthys, N., Joosen, W., Hughes, D., Vučinić, M.: Towards efficient publish-subscribe middleware in the IoT with IPv6 multicast. In: <i>Proceedings of 2016 IEEE International Conference on Communications</i> . IEEE, USA (2016)	23
S6	Shekhar, S., Chhokra, A., Sun, H., Gokhale, A., Dubey, A., Koutsoukos, X.: URMILA: A performance and mobility-aware fog/edge resource management middleware. In: <i>Proceedings of the 22nd IEEE International Symposium on Real-Time Distributed Computing</i> , pp. 118–125. IEEE, USA (2019)	12
S7	Jeon S., Jung, I.: Mint: Middleware for cooperative interaction of things. <i>Sensors</i> 17 (6) (2017)	32
S8	Cecchinell, C., Fouquet, F., Mosser, S., Collet, P.: Leveraging Live Machine Learning and Deep Sleep to support a self-adaptive efficient configuration of battery powered sensors. <i>Future Generation Computer Systems</i> 92 , 225–240 (2019)	11
S9	Padhy, S., Chang, H.-Y., Hou, T.-F., Chou, J., King, C.-T., Hsu, C.-H.: A middleware solution for optimal sensor management of IoT applications on LTE devices. In: J.-H. Lee, S. Park (eds.) <i>Quality, Reliability, Security and Robustness in Heterogeneous Networks</i> , ser. <i>Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering</i> , vol. 199, pp. 283–292. Springer International Publishing, Switzerland (2017)	0
S10	Oliveira, E.A., Delicato, F., Mattoso, M.: An energy-aware data cleaning workflow for real-time stream processing in the Internet of Things. In: <i>Anais do IV Workshop de Computação Urbana</i> , pp. 71–83. SBC, Brazil (2020)	1
S11	S. Pasricha.: Overcoming energy and reliability challenges for IoT and mobile devices with data analytics. In: <i>Proceedings of the 31st International Conference on VLSI Design and 17th International Conference on Embedded Systems</i> , pp. 238–243. IEE, USA (2018)	4
S12	Sarkar, C., Rao, V.S., Venkatesha Prasad, R., Das, S.N., Misra, S., Vasilakos, A.: VSF: An energy-efficient sensing framework using virtual sensors. <i>IEEE Sensors Journal</i> 16 (12), 5046–5059 (2016)	31
S13	Aazam, M., Zeadally, S., Feo Flushing, E.: Task offloading in edge computing for Machine Learning-based smart healthcare. <i>Computer Networks</i> 191 (2021)	23
S14	Mukherjee, A., Dey, N., De, D.: EdgeDrone: QoS aware MQTT middleware for mobile edge computing in opportunistic Internet of Drone Things. <i>Computer Communications</i> 152 (2020)	39
S15	Li, W., Delicato, F.C., Pires, P.F., Lee, Y.C., Zomaya, A.Y., Miceli, C., Pirmez, L.: Efficient allocation of resources in multiple heterogeneous wireless sensor networks. <i>Journal of Parallel and Distributed Computing</i> 74 (1), 1775–1788 (2014)	107
S16	Podnar Zarko, L., Antonic, A., Pripuzic, K.: Publish/subscribe middleware for energy-efficient mobile crowdsensing. In: <i>Proceedings of the 2013 ACM Conference on Pervasive and Ubiquitous Computing Adjunct Publication</i> , pp. 1099–1110. IEEE, ACM (2013)	46
S17	Al-Madani, B., Shahra, E.: An energy aware platform for IoT indoor tracking based on RTPS. <i>Procedia Computer Science</i> 130 , 188–195 (2018)	10
S18	Banouar, Y., Monteil, T., Chassot C.: Analytical model for adaptive QoS management at the middleware level in IoT. In: <i>Proceedings of the 2017 IEEE Symposium on Computers and Communications</i> , pp. 1201–1208. IEEE, USA (2017)	3
S19	Huang Z., Lin, K.J., Han L.: An energy sentient methodology for sensor mapping and selection in IoT systems. In: <i>Proceedings of the 23rd IEEE International Symposium on Industrial Electronics</i> , pp. 1436–1441. IEEE, USA (2014)	14
S20	Pasricha S.: Overcoming energy and reliability challenges for IoT and mobile devices with data analytics. In: <i>Proceedings of the 31st International Conference on VLSI Design and 2018 17th International Conference on Embedded Systems</i> , pp. 238–243. IEEE, USA (2018)	4
S21	Ramachandran, G.S., Proença, J., Daniels, W., Pickavet, M., Staessens, D., Huygens, C., Joosen, W., Hughes, D.: Hitch Hiker 2.0: A binding model with flexible data aggregation for the Internet-of-Things. <i>Journal of Internet Services and Applications</i> 7 (2016)	13
S22	Elhabbash, A., Elkhathib, Y.: Energy-aware placement of device-to-device mediation services in IoT systems. In: H. Hacid, O. Kao, M. Mecella, N. Moha, H.Y. Paik (eds.) <i>Service-Oriented Computing. Lecture Notes in Computer Science</i> , vol. 13121, pp. 335–350. Springer Nature Switzerland AG, Switzerland (2021)	0

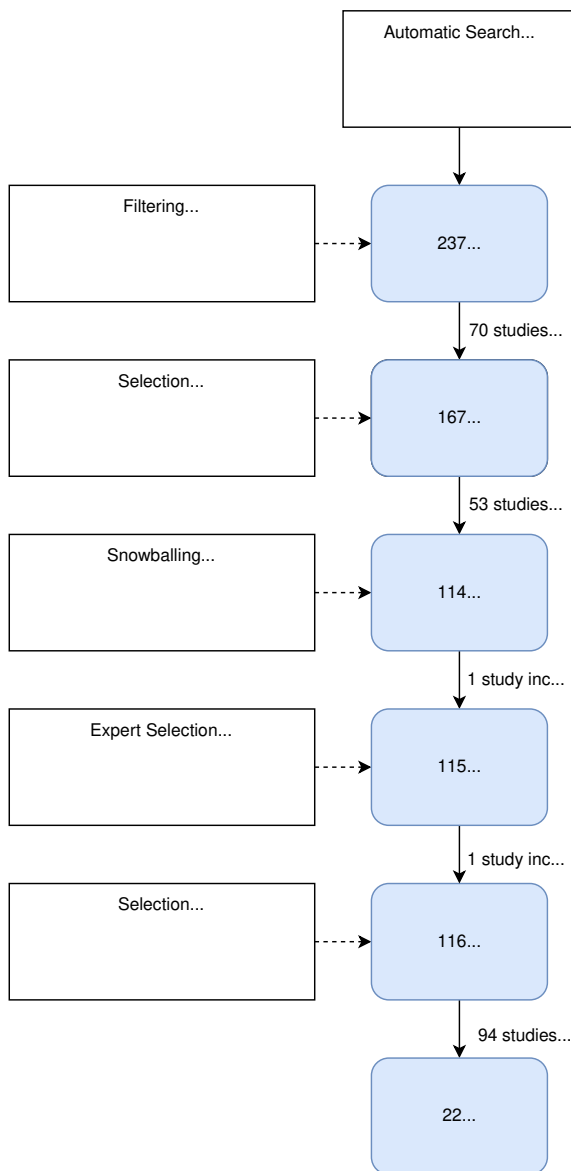


Fig. 2 Steps to select the relevant primary studies

4 Results and discussion

This section summarizes and discusses the results of the SLR considering the four RQs introduced in Section 3 and the data extracted and synthesized from the analyzed primary studies. Answers to each RQ concern strategies, abstractions, evaluation, and target of the IoT middleware.

4.1 Energy-aware and energy-efficient strategies in IoT middleware

The analysis of data extracted from the selected primary studies identified several strategies and techniques for energy efficiency in IoT middleware, answering RQ1. Table 2 lists these strategies and techniques.

The main strategies used in the studies for providing energy efficiency and awareness are *network adaptation* (9/22) and *task offloading* (8/22). Network adaptation refers to introducing new protocols or modifying existing ones, making network optimizations (e.g., choosing the network technology), and reducing network usage at the middleware level. As examples of network adaptations, study S4 modifies the Data Distribution Service (DDSTM) protocol [34] to improve energy efficiency, while studies S5, S9, and S12 propose a protocol adaptation by using new algorithms. In study S5, the capabilities of IPv6 multicast are used with a publish-subscribe interaction, resulting in lower network and energy consumption. Task offloading means using the network to transfer processes or data to other locations. For example, an application running on a mobile phone could send data to a server or other mobile phones for data processing purposes. Studies S1, S2, and S6 propose offloading processes or code to other parts of the system (such as servers and fogs) to save energy on some nodes. Similarly, study S11 runs a virtual machine in a cloud environment to execute applications instead of running them on local network devices.

Active node selection is a strategy used by IoT middleware for sensor networks (3/22). In active node selection, a given node (connected objects, cloud, fog, etc.) can be selected to process data, and this node can change when it is necessary to extend the lifetime of the entire IoT system. This refers to balancing the energy usage across multiple objects in the same network and knowing the energy capabilities of each object. Therefore, the system will select the ones with the highest energy available to process data, thus increasing the time the system will be fully alive (with all nodes working). Studies S8 and S12 propose changing the number of active nodes in a sensor network according to observations sent by these nodes and the overall communication (data) over the network. In contrast, study S4 proposes simulating the energy available in each node of a sensor network and periodically selecting those that are active.

Machine Learning is used in 3/22 studies to build a model based on input data towards making adaptations to save energy. These data can be made of information such as network conditions, CPU load in devices, amount of device communication, data sent by devices, etc. Building the model allows for adaptations to the application's behavior to save energy or allow the model to improve and better manage data to provide the expected energy saving. Study S8 uses Machine Learning to increase the energy efficiency of the entire network and the lifespan for long periods. It does this by determining an optimal configuration of sensors for extending their battery life, using sensor sampling frequency and network usage data.

The *data filtering* capability offered by some middleware (5/22 studies) proposes processing data to reduce the

Table 2 Strategies and techniques for energy efficiency in IoT middleware

Strategies and techniques	Studies																					
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22
Network adaptation	×	×	✓	✓	✓	×	✓	×	✓	×	×	✓	×	✓	✓	×	×	✓	×	×	×	×
Task offloading	✓	✓	×	×	×	✓	×	×	×	×	✓	×	✓	×	×	×	×	×	✓	✓	×	✓
Active node selection	×	×	×	✓	×	×	×	✓	×	×	×	✓	×	×	×	×	×	×	×	×	×	×
Machine Learning	×	×	×	×	×	×	×	✓	×	×	×	×	✓	×	×	×	×	×	×	✓	×	×
Data filtering	×	×	×	×	×	×	×	×	×	✓	×	×	×	×	✓	✓	✓	×	×	×	✓	×

amount of data transmitted or to limit the size of the message according to specific criteria (network load, CPU usage, energy usage, etc.). Studies S10, S15, S16, S17, and S21 use a data filtering strategy to continuously remove unused data to reduce the amount of data to be processed/transmitted, thereby reducing energy consumption in the system. For example, study S10 provides energy-aware data collection that can reduce the amount of data processed and sent to the network while maintaining accurate data flow for applications that need high QoS, such as real-time applications.

Main findings (RQ1). Several strategies and techniques have been proposed in the literature for energy efficiency in IoT middleware. Most studies have focused on performing adaptations at the network level or offloading tasks. Moreover, most studies use only one strategy, i.e., combining different strategies and techniques has not been addressed in detail.

4.2 Abstractions for energy-awareness or energy efficiency in IoT middleware

RQ2 concerns identifying any synergy between applications (i.e., at the software level) and IoT middleware when considering energy-awareness or energy efficiency. Only four studies (S2, S3, S7, and S20) focus on providing ways for an IoT application to easily use energy-awareness (S2) or energy efficiency (S3, S7, and S20) strategies with the middleware through programming abstractions. Study S2 proposes an energy-aware abstraction, while studies S3, S7, and S20 propose energy-efficient abstractions. These proposals are presented as libraries, frameworks, or well-defined APIs abstracting away the specific details needed for an energy-aware/efficient implementation from the developer.

In study S2, application developers provide their energy constraints for component offloading (i.e., minimum battery level) through a configuration file, and application developers and the middleware calculate the energy requirement for choosing the hosts best suited for offloading. In study S3, an asynchronous API is proposed to send and receive data to multiple peers. Applications choose between two methods that implement different strategies for energy efficiency

purposes: either to periodically distribute small context data to all their neighbors or to transfer a large volume of data to specific peers at one time. The middleware transparently chooses the most efficient device-to-device wireless network technology (e.g., Wi-Fi or Bluetooth) in terms of energy for the application's use. In study S7, the middleware provides a high-level API for developing IoT device applications. The middleware transparently chooses the most efficient communication strategy and adapts the application's behavior according to the data received from neighboring devices.

The solutions providing energy-aware/efficient abstractions (S2, S3, S7, and S20) are based on neighboring devices that periodically send data that are used or analyzed by the middleware to manage the energy-awareness/efficiency in the application. The studies work with those data to better communicate between the application and neighboring devices.

Main findings (RQ2). Most studies do not consider any energy-aware/efficient abstraction, leading to a concern about how easily an IoT application can enable an energy-efficient/aware strategy through middleware.

4.3 Evaluation of energy-aware/efficient IoT middleware

RQ3 is interested in identifying how the energy efficiency/awareness of IoT middleware and IoT systems have been evaluated through experimentation or simulation. Seven of the selected studies considered using simulation to evaluate the energy consumption of the middleware. In contrast, fifteen studies present an evaluation based on testbeds and scenarios that use real-world sensors and experiments based on concrete implementations. This indicates a tendency to experiment with concrete solutions, gathering information from real-case scenarios.

The data extraction process also provided information regarding the current state of the middleware: whether the middleware is implemented and working in an IoT system or an abstract architecture presents it with no concrete implementation. Nineteen of the selected studies described an implemented middleware deployed and used in a real-world scenario. In contrast, three studies explained the middleware

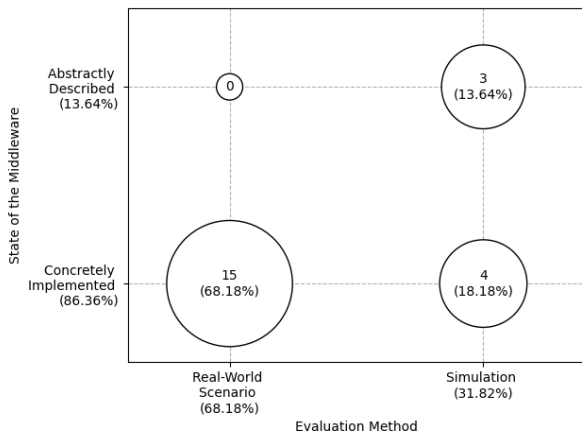


Fig. 3 Evaluation method and state of the implementation

and proposed models without a concrete implementation in IoT systems. Fig. 3 shows the correlation between the evaluation methods and the state of the energy-aware/efficient middleware proposed in the selected primary studies. It is noteworthy that most of the concretely implemented middleware has been experimented with in real-world scenarios, while the more abstract proposals have been evaluated only via simulation.

Main findings (RQ3). Most solutions present a concrete implementation and can be used in real-world scenarios with IoT systems. In contrast, there are a few studies addressing evaluation with simulation.

4.4 Target of energy efficiency

RQ4 aims to identify the target of the energy efficiency of the IoT middleware. Four main targets were observed: (i) *end-user application*, representing the device used by the user to access an IoT application; (ii) *connected objects*, such as sensors and actuators; (iii) *server*, referring to middleware usually deployed in fogs or clouds; and (iv) *sensor network*, related to techniques to reduce energy consumption over the whole sensor network. Table 3 summarizes the target of the selected primary studies concerning energy efficiency.

The middleware presented in studies S1 and S11 saves energy at the server level. For instance, the middleware described in study S1 has data processed at the cloud/fog level, and only the necessary data is sent to the server. Ten other studies operate at the end-user application side, and nine studies focus on the connected object side. For example, study S8 proposes a deep sleep of connected objects to save network usage. Studies S4, S8, S12, S15, S17, and S19 propose to reduce the energy consumption in the sensor net-

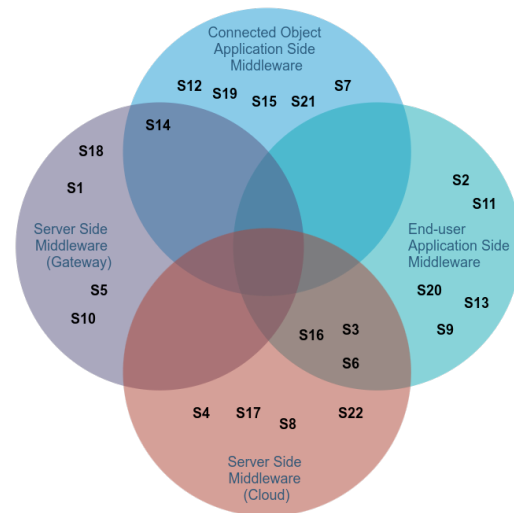


Fig. 4 Middleware deployment locations addressed in the selected primary studies

work, e.g., by changing communication among nodes in the same network.

In the selected studies, the middleware in the IoT system is deployed in different locations (see Fig. 4). Studies S2, S9, S11, S13, and S20 propose deploying the middleware at the end-user application side. On the other hand, studies S3, S6, and S16 propose a middleware deployed in both the end-user applications and the cloud, while studies S7, S12, S15, S19, and S21 deploy the middleware in the connected objects. It is also possible to notice that servers have been used to deploy the middleware without being the target of energy efficiency in the proposals.

Studies S4, S8, S17, and S22 present middleware on the cloud side. In contrast, studies S1, S5, S10, and S18 present middleware deployment in a gateway, whereas study S14 deploys its middleware both in the gateway and in the connected object. The choice to deploy the middleware on the cloud, gateway, or other parts of a system is highly influenced by the implemented solution, and there is no rule for choosing the *best* location. Furthermore, studies S3, S6, and S16 deploy their middleware in multiple places so that the placement of the middleware is related to how the energy-aware/efficient strategy works.

Main findings (RQ4). Most of the selected studies present solutions working on the end-user application side, thereby showing a more significant concern related to the lifetime of battery-constrained devices (e.g., smartphones). A few studies are concerned with more than one target, leading to issues regarding the distribution of energy awareness and efficiency in an IoT system.

Table 3 Target of energy efficiency in IoT middleware

Energy efficiency target	Studies																					
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22
End-user application	×	✓	✓	×	✓	✓	×	×	×	✓	✓	×	✓	×	×	✓	×	×	×	✓	✓	×
Connected objects	×	×	×	×	×	×	✓	✓	✓	✓	×	×	×	✓	✓	×	✓	×	✓	×	×	✓
Server	✓	×	×	×	×	×	×	×	×	×	✓	×	×	×	×	×	×	✓	×	×	×	×
Sensor network	×	×	×	✓	×	×	×	✓	×	×	×	✓	×	×	✓	×	✓	×	✓	×	×	×

5 Challenges and perspectives

This section raises some potentially relevant directions for research and development regarding energy efficiency in IoT middleware, through analysis of the selected corpus and the obtained findings. The discussion here focuses on (i) how to identify energy-consuming components used by the middleware, (ii) security concerns related to energy efficiency, and (iii) how middleware can provide benefits to IoT applications regarding energy efficiency.

Identifying energy-consuming components. The selected primary studies usually focused on a specific component and optimizing it towards reducing energy consumption, but this leaves a gap for energy optimization in other system parts. Some techniques - such as static code analysis [43], profilers to detect software energy and performance bugs [30], program-data tracking (transformation, propagation, and consumption) [48], and diagnosis of end-user events [25] - have been proposed in recent years, aiming at easing the identification of energy-consuming components. Although this work does not have a specific RQ for identifying those components, this issue is relevant since some studies provide architectural models with many components. However, they focus on reducing the energy consumption in one type of component, rather than globally. Energy efficiency must be considered across the entire IoT architecture in order to achieve an acceptable performance [1]. Exploring how to identify components that use a significant amount of energy may drive further research in energy-efficient IoT middleware.

Addressing the energy cost of security. Security is acknowledged as a significant concern for the IoT [14]. However, implementing cryptography or any other security strategy at the middleware level requires significant processing from hardware. Middleware works as an intermediary among components, and data passing through it could be encrypted or need to be encrypted by it. There is a need to consider how encryption may work in energy-efficient IoT middleware. None of the primary studies analyzed in this SLR has addressed security and considered the energy consumption of security-related components. As many applications and devices have tight constraints regarding energy resources, implementing traditional security mechanisms to work with them is not straightforward [17]. The

inherent characteristics of security also bring challenges when implementing communication between middleware or applications and devices. Some open problems are (i) lightweight device authentication, (ii) denial-of-service attacks, and (iii) end-to-end security [29]. The impact of potential future solutions to the security challenges is critical and encourages further research in this direction.

Using energy-aware/efficient IoT middleware in application development. When developing IoT applications atop middleware platforms, a developer may face some challenges regarding their use. Energy-efficient solutions might work on a low level of abstraction, thus requiring an IoT application developer to know how to address this concern. From the perspective of application developers, the middleware can provide multiple communication protocols, software development kits (SDKs), high-level programming abstractions, etc., thereby easing the task of application developers when dealing with energy efficiency in IoT applications. The selected primary studies analyzed in this SLR do not directly address such issues, although studies S2, S3, and S7 do provide application abstractions to facilitate the energy-efficiency of their middleware. Therefore, an important research direction to foster energy efficiency in IoT middleware is providing relevant energy-aware abstractions. Energy-aware abstractions can enable developers to express energy requirements and evaluate energy consumption. Furthermore, energy-aware abstractions may increase efficiency as the awareness brings a broader view of where and how the many resources (CPU, network, energy, etc.) used by middleware behave in terms of energy consumption.

6 Threats to validity

External validity. External validity essentially concerns the ability to generalize the obtained findings. The most significant threat to the external validity of this SLR concerns the possibility of missing relevant primary studies. To reduce this threat, five of the most used publication electronic databases in Computer Science and Engineering were considered in this study. Nonetheless, there are still limitations. First, some studies may not have been retrieved due to technical limitations of the automated search engines of the electronic publication databases, on which there is no precise control. Second, these databases do not represent

an exhaustive list of publication sources, so that other ones could also have been considered. Third, this SLR did not consider gray literature (e.g., white papers, technical reports, dissertations, non-peer-reviewed papers, etc.) as a source of studies. Despite the increasingly acknowledged value given to gray literature as a source of evidence, not considering it is not necessarily an additional threat since peer review processes are a standard requirement for high-quality publications. Fourth, the choice of the keywords might impact the search as other similar and alternative terms could be used in the search string. Some studies also consider middleware, but with a different definition and meaning from the one in this work.

Internal validity. Internal validity focuses on the conduction of the SLR, particularly data extraction and synthesis, and any factor that may have caused bias in the process. Two potential threats to internal validity are (i) imprecision in data extraction and (ii) bias in data synthesis, mainly because not all studies clearly and sufficiently describe the information extracted from them. Therefore, some information regarding the data items in the data extraction and synthesis processes needed to be inferred. The data extraction items were precisely defined in the study protocol to minimize these threats. In addition, discussions were held to clarify any inconsistencies.

Construct validity. Construct validity is related to the capacity of the study design to answer the investigated RQs. The selection of the primary studies according to the inclusion and exclusion criteria (see Section 3) was rigorously carried out to ensure that these studies were indeed suitable for answering the RQs. All researchers involved in this study extensively discussed these criteria and the studies resulting from the selection steps.

Conclusion validity. Conclusion validity is mainly concerned with the analysis of the obtained results, being related to the extent they can be regarded as correct. It is also concerned with the rigor and reproducibility of the process used to draw conclusions from these results. A well-defined protocol was established to guide all the activities carried out in this study and mitigate potential threats to conclusion validity. This protocol was also extensively discussed with researchers having expertise in systematic literature reviews and mapping studies.

7 Conclusion

The IoT paradigm offers promising opportunities to improve daily life through continuous, dynamic cooperation between systems and physical objects. However, properly dealing with the development of IoT systems means providing solutions to significant challenges such as energy efficiency and resource consumption while facilitating development. Addressing the energy-efficiency challenge

at the middleware level can reduce the energy consumption of systems supported by middleware while relieving application developers from this concern. Furthermore, energy-awareness in middleware will impact the efficiency of the applied strategies as there will be more information about where and how the energy is being used, providing valuable knowledge for lowering the energy usage through middleware.

This paper presented the results of an SLR to identify and understand essential features for energy efficiency and energy-awareness in IoT middleware. The systematic selection and analysis of 22 studies has demonstrated increasing concern for energy efficiency in IoT middleware. However, a small part of the selected corpus also considers energy-related issues from the perspective of developing IoT applications. Among the strategies for providing IoT middleware with energy efficiency and awareness, active node selection and Machine Learning are not commonly used by the existing approaches. These merit more consideration when proposing energy-efficient/aware strategies for IoT middleware.

As the adoption of energy efficiency in IoT middleware is a recent topic, this SLR can open perspectives for relevant issues to be addressed in future research. These issues are: (i) how to consider energy-awareness in multiple components of an IoT system; (ii) the most suitable strategies depending on the proposed energy-efficient solution; and (iii) how IoT applications can use the energy-efficient and energy-aware mechanisms. By identifying important energy efficiency features to be addressed in IoT middleware, this study can contribute to a more effective design of middleware platforms considering energy consumption by both the researchers and practitioners interested in this topic.

Compliance with ethical standards

Not applicable

Conflicts of Interest

Not applicable

A Summary of selected primary studies

Study **S1** considers different task offloading strategies. Tasks are the processes that transfer data from connected IoT objects to a deployed fog, cloud, or their collaboration (FC). A gateway might also be used to communicate between fog, cloud, and the FC. The proposed strategies use either a random (asynchronous multithreaded) or a first-come/first-served (synchronous single-threaded) task distribution. The fog nodes can communicate with each other to better distribute the tasks. When using the gateway, the decision is made to send large datasets to the

cloud and small datasets to the fog. The study also concludes that using a gateway with the FC strategy provides better results in terms of energy consumption.

Study **S2** proposes a microservice-based middleware that distributes executable code across nearby mobile devices. The mobile device that deploys the code is selected based on the available device's resources. The study compares the service initiation time (the first use of the service), executing JavaScript or native services that provide image processing, Internet sharing, and GPS sharing for mobile devices across the network. Results from an empirical evaluation show that executing services on nearby devices can improve the energy consumption of the mobile device that calls for the execution of these services.

Study **S3** proposes Omni, a device-to-device middleware with the periodic adaptive discovery of neighbor devices using lightweight discovery mechanisms in wireless local area networks. Discovered devices are connected when data needs to be transferred, and the communication technology can change to the methods chosen by the application developer according to the volume of these data. The authors describe an evaluation regarding energy consumption and latency on the discovery technology in different scenarios. They conclude that changing the protocol for different amounts of data and finding the best discovery technology can improve energy efficiency.

Study **S4** proposes EatDDS, an energy-aware data distribution service (DDS) dedicated to wireless sensor networks (WSN). EatDDS aims to equitably share the consumption among the nodes to improve the TinyDDS energy-efficient protocol. A TinyOS simulator for WSN is modified to become energy-aware in the study. Simulation results show that using EatDDS can improve network lifetime compared to TinyDDS. The network lifetime can be seen as energy efficiency in battery-constrained environments since the goal is to reduce the energy utilization to keep the IoT system working as long as possible.

Study **S5** proposes an adaptation of a publish-subscribe middleware by adding a layer between the broker and the client applications (in an IPv6 network) to send notifications via IPv6 multicast rather than using several point-to-point messages. The proposed framework maps application-layer subscriber groups to network layer multicast groups. The proposal reduces (i) the network overhead when there are many consumers for the same group on the same network (edge side) and (ii) the energy consumption on the edge broker node.

Study **S6** proposes URMILA (*Ubiquitous Resource Management for Interference and Latency-Aware services*). This middleware makes effective trade-offs between using fog and edge resources while ensuring that the latency requirements of the IoT applications are met. URMILA works by transferring tasks from applications to fogs when the client needs to reduce the processing on the end-user device and thus reduce the energy consumption. It determines if the request will be processed locally or remotely on the selected fog server. The study shows that using URMILA contributes to meeting application requirements while introducing energy efficiency.

Study **S7** proposes MinT (*Middleware for Cooperative Interaction of Things*), a middleware in which IoT devices directly connect to peripheral devices and construct a local or global network where they share data in an energy-efficient way. MinT provides an abstract layer, a system layer, an interaction layer, and a high-level API for applications. The study describes an evaluation comparing the proposed solution with an existing message processing middleware and shows that MinT can reduce IoT devices' latency and power consumption.

Study **S8** proposes determining an optimal configuration of sensors for extending their battery life. The solution is to optimize sensor usage, network usage, and measurement quality in terms of (i) configuring the sensors' sampling frequency with Machine Learning and (ii) optimizing network usage according to the frequency of requests from the deployed software applications. The study shows measurements according to the sensors' battery life and how their solution improves the lifetime of a WSN.

Study **S9** proposes a middleware to minimize the total energy consumption of an IoT application while ensuring that the requested accuracy is met. The middleware identifies the sensors that consume the least energy while satisfying the sensing requirements and maximizing the overall accuracy under an energy budget. Simulations demonstrate how the algorithm works and indicate that the proposed algorithms outperform some existing solutions.

Study **S10** proposes a data stream processing workflow to be deployed at the network's edge to (i) provide an energy-aware data collection component to reduce the network traffic, (ii) implement a density-based clustering component to efficiently perform the data cleaning task by quickly identifying and removing outliers from the data stream, and (iii) deliver a curated secondary data stream output that can be consumed by business applications, services or additional workflow tasks with real-time processing requirements. The study addresses the reduction of device power consumption, the enforcement of data accuracy and completeness, and real-time responses.

Study **S11** proposes a data analytics middleware for energy-efficient execution of various applications on commodity mobile devices. The proposed solution is to apply different Machine Learning algorithms to show different use cases and how the chosen algorithm impacts the energy efficiency of the IoT system. The middleware's energy efficiency was experimented with in different scenarios considering battery lifetime, accuracy, response time, and adaptation to user behavior.

Study **S12** proposes the *Virtual Sensing Framework* (VSF) to reduce the interactions among the nodes of a WSN and hence the network's energy consumption. The solution works by keeping some nodes in the network in a low-power sleep state and running a heuristic algorithm to select the best nodes to improve the lifetime of the WSN. The study uses three metrics to evaluate the performance, namely (i) the number of transmitted data packets, (ii) the accuracy of prediction, and (iii) the energy expenditure of the nodes.

Study **S13** proposes the use of edge computing to provide smart and opportunistic healthcare (oHealth). The solution uses Machine learning-based task offloading in edge computing with real data traces for several healthcare and safety-related scenarios. An evaluation shows how energy-efficient this solution is compared to not using task offloading.

Study **S14** proposes a message transfer mechanism using drone nodes that participate as edge computing components. This transfer mechanism is introduced as enhanced MQTT and MQTT-SN. An evaluation of the solution with a real testbed showed that the enhancement of MQTT and MQTT-SN use less energy among other resources. However, for the MQTT/MQTT-SN broker, there is an increase in memory consumption as a drawback, which could lead to problems when there are many nodes in the network.

Study **S15** proposes a middleware platform that manages heterogeneous WSNs and efficiently shares their resources to increase the network's lifetime. The solution is a new resource allocation algorithm called SACHSEN (*reSource AlloCation in Heterogeneous Sensor Networks*) that controls the distributed application, and coordinate nodes in the execution of submitted sensing tasks in an energy-efficient and QoS-enabled way. They show in their evaluation that when compared to other algorithms, SACHSEN produces promising results in terms of both application performance and energy efficiency depending on the scenario of the WSN.

Study **S16** proposes a mobile crowdsensing application for community sensing where sensors and mobile devices work together to provide data of interest to observe and measure events across a large geographic area. The solution uses the MoPS middleware, which provides energy efficiency as it suppresses the transmission of sensor readings from Mobile Internet-connected Objects (MIOs) and filters out the data that are not needed by the application. The evaluation used real user traces and showed that the solution could potentially save energy

as the amount of data transferred from the cloud to the mobile applications and vice-versa is significantly lowered.

Study **S17** proposes an energy-aware platform for indoor tracking using the RSS (*Receive Signal Strength*) algorithm, which is used to measure values such as position, distance, and others to provide a multi-hop protocol used between publishers and subscribers. The solution uses the sensor Data Distribution Service (sDDS) middleware to interconnect all system components. The evaluation showed that RSS has reasonable accuracy and low energy consumption when calculating values such as distance and position among sensors, which could be acceptable depending on the application.

Study **S18** proposes the autonomic management of QoS in an IoT middleware to optimize the energy consumption of IoT entities (gateway) while maintaining the QoS constraints of critical IoT applications. The solution uses the MAPE-K autonomic loop as an analytical model for the OM2M middleware platform entities to estimate their performance metrics (response time, queue size, etc.) depending on the arrival rate of requests and monitoring components to detect QoS degradation. The evaluation showed that autonomic management could react to constraints of applications. Moreover, for cases requiring lower energy consumption, the solution is able to react and use energy-efficient mechanisms such as CPU core deactivation.

Study **S19** proposes using the WuKong middleware with a new sensor selection methodology to minimize the total communication energy consumption and balance the energy costs on devices over a network to increase the system lifetime. The solution uses a service collocation and sensor selection algorithm to minimize the energy consumption and balance the energy usage over a network, increasing its lifetime. The evaluation relied on simulation with a collocation algorithm, a sensor selection algorithm, or both simultaneously. The results have shown that, depending on the number of sensors, the energy saving can be high or low, but it reduces energy consumption to a certain degree and can increase the system's lifetime, even if for a small margin.

Study **S20** proposes to design and deploy data analytics and Machine Learning to improve the energy efficiency of IoT systems through middleware. The solution uses energy-efficient/aware mechanisms such as mobile-to-cloud offloading, user-interaction aware optimizations, and spatiotemporal context-aware optimization. The mobile-cloud offloading is used to support high-end mobile data processing applications and enable them to offload mobile computations to the cloud. The user-interaction aware optimization is provided by the AURA middleware, which takes advantage of user idle time between interaction events of the foreground application to optimize CPU and backlight energy consumption. The spatiotemporal context-aware optimization is used to transparently capture contextual data attributes (day, hour, etc.), spatial environment data (e.g., ambient light, Wi-Fi RSSI, 3G/4G signal strength), and device state (e.g., battery status, CPU utilization) in order to remove unnecessary data. The solution was evaluated by comparing many Machine Learning algorithms, showing the gains in energy saving of the used mechanisms.

Study **S21** proposes a component binding model called Hitch Hiker that allows for data aggregation over communications in a network. The solution allows application developers to specify high-priority remote bindings that generate radio transmissions or low-priority remote bindings that communicate exclusively using the data aggregation overlay, resulting in no additional transmissions. The evaluation compared the solution model with other models with similar behavior and showed that using Hitch Hiker to route low-priority traffic reduces energy consumption.

Study **S22** proposes an algorithm to use the network structure to compute the placement of mediation services to minimize the energy consumed by the interactions between IoT devices through formulating this placement as an integer linear programming (ILP) problem. The solution allows the energy consumption among many sensors of a

network to be calculated and then to place mediation services based on environmental changes. The evaluation of this algorithm is compared to other three algorithms and has shown that it minimizes the energy consumption.

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